

Workshop on Spectroscopy of the Martian Surface: What Next?

Held at

**Lunar and Planetary Institute, Houston, TX
June 10-11, 1999**

Edited by

**L. Kirkland, J. Salisbury, J. Mustard,
R. Clark, P. Lucey, and S. Murchie**

Sponsored by

**Lunar and Planetary Institute
JPL Mars Program Office**

Convener

Laurel Kirkland

LPI Contribution No. 1149

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Introduction

Members of the Mars infrared spectral community desired to assess what spectral instrument will best serve the Mars program and spectral community after the successful flight of currently planned instruments. It was felt this issue needed to be addressed, given the shift of the NASA Mars program toward a search for regions conducive to the preservation of biomarkers, and the desire for sample return. To this end, leaders of the planetary community with expertise in spectroscopy and remote mineral identification met to discuss the state of understanding of Mars surface composition, and to assess what critical gaps may exist: 1) after the successful completion of planned measurements of Mars; and 2) in research programs to support investigations of the current and planned data sets. Participants also discussed the proposed Mars airplane. This report summarizes our consensus.

To support the selection of landing sites that may preserve biomarkers, participants agreed that the most critical gap that will remain is a spectral data set containing very high information content spectra of targeted regions.

Mineralogy is an essential tool to assess ancient and modern environments on Mars that may have been conducive to the support and preservation of life and biomarkers. Reflectance and emission spectroscopy remain the most capable method for remote mineral identification. Experience gained from spectral data sets of Mars and Earth has shown that an unambiguous interpretation requires spectra with both high spatial resolution and very high information content. High information content is obtained by measuring with broad spectral range, high spectral resolution, and high signal to noise ratio.

Participants concluded that there are two critical gaps in the ability of the community to interpret current and planned spectral data sets. First is a lack of a widely accepted method to quantitatively examine remotely sensed spectra. Second is the lack of adequate spectral libraries available to the entire community that contain the needed range of minerals, coatings, and particle sizes.

Selecting among potential landing and sample return sites will be aided by a clear, unambiguous interpretation of spectra measured from orbit. To provide adequate support for the landing site selection process, we recommend the measurement from orbit of high information content spectra of targeted regions, and the development of the two listed research areas. This will provide essential tools in the phased approach to Mars exploration that NASA has developed. Additional details on workshop recommendations are contained in the Letters within this report. We strongly encourage NASA and the Mars community to consider these recommendations in planning for future research programs.

Sincerely,

Participants of the workshop, "*Spectroscopy of the Martian Surface: What Next?*"

Jim Bell	Diana Blaney	Phil Christensen	Ben Clark	
Roger Clark	Stephane Erard	Jack Farmer		William Farrar
Rudy Hanel	Gary Hansen	Ken Herr	Eric Keim	
Laurel Kirkland	Melissa Lane	Paul Lucey		Richard Morris
Scott Murchie	John Mustard	Carle Pieters		Jack Salisbury
Steve Saunders	Allan Treiman	Steve Young		

Participant	Affiliation, and instruments built/building
Jim Bell	Cornell University
Diana Blaney	Jet Propulsion Laboratory
Phil Christensen	Arizona State University; 1997 TES PI; 2001 THEMIS PI; '01, '03, '05 Mini-TES PI
Ben Clark	Lockheed-Martin
Roger Clark	USGS; 1997 TES Co-I
Stéphane Erard	CNES
Jack Farmer	Arizona State University
William Farrand	Space Science Institute
Rudy Hanel	GSFC (retired); 1971 IRIS PI
Gary Hansen	U. Hawaii
Ken Herr	Aerospace Corporation; 1969 IRS Co-I
Eric Keim	Aerospace Corporation
Laurel Kirkland	Lunar and Planetary Institute; Convener
Melissa Lane	NASA-JSC
Paul Lucey	U. Hawaii
Richard Morris	NASA-JSC

Scott Murchie	Johns Hopkins U.-Applied Physics Laboratory
John Mustard	Brown University
Carlé Pieters	Brown University
Jack Salisbury	Johns Hopkins University
Steve Saunders	Jet Propulsion Laboratory
Allan Treiman	Lunar and Planetary Institute
Steve Young	Aerospace Corporation

IRS = 1969 Mariner Mars 6/7 Infrared Spectrometer

IRIS = 1971 Mariner Mars 9 Infrared Interferometer Spectrometer

TES = 1997 Global Surveyor Thermal Emission Spectrometer

Co-I = Co-Investigator

PI = Principal Investigator

Historical Note

This workshop had an unusual breadth of researchers present, and included expertise in spectroscopy of Mars, Earth, and the moon; from the both NASA and the DOD/Intelligence community; and in laboratory spectral research and computational spectral analysis.

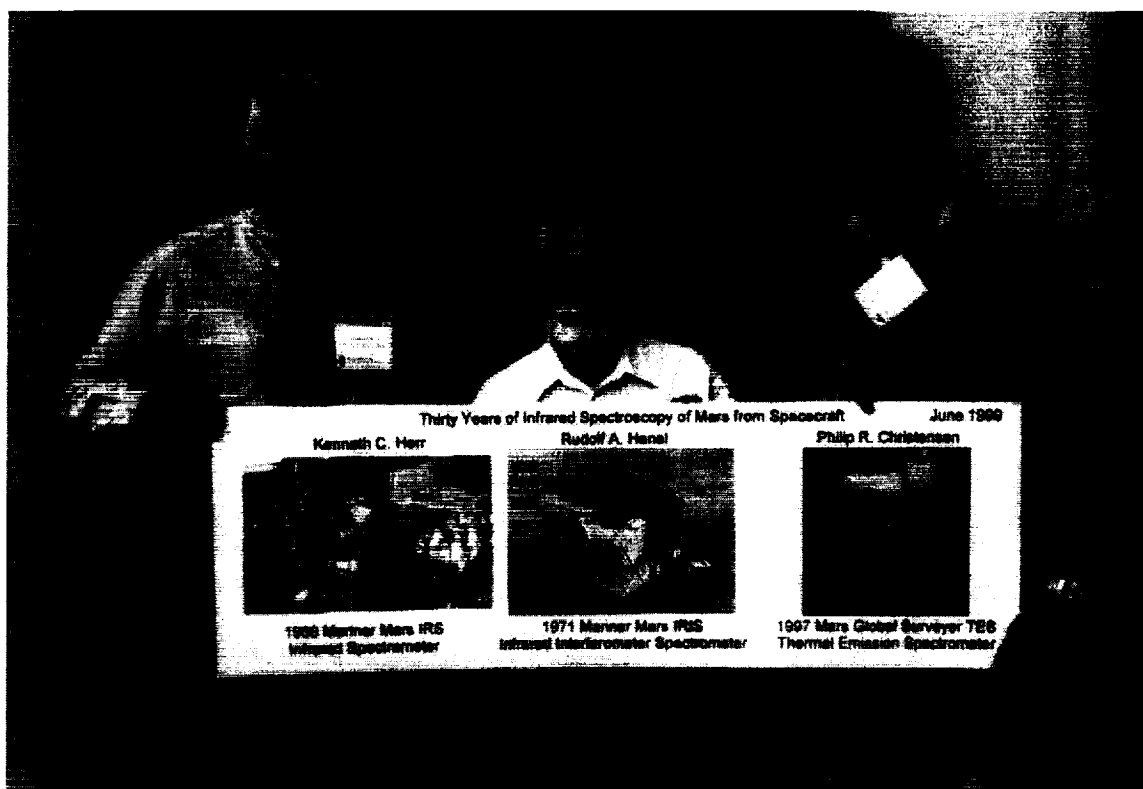
However, an interesting historical note was the presence of all three builders of the only thermal infrared spectrometers ever sent to Mars. It is the first, and will perhaps be the only time, that all three have been together:

Builders of thermal infrared spectrometers flown to Mars, shown left to right below:

Kenneth C. Herr (1969 Mariner Mars 6/7 Infrared Spectrometer, *IRS*)

Rudolf A. Hanel (1971 Mariner Mars 9 Infrared Interferometer Spectrometer, *IRIS*)

Philip R. Christensen (1997 Global Surveyor Thermal Emission Spectrometer, *TES*)



Click [here](#) for larger image

*Photo Credit: Debra Rueb, LPI Staff Photographer
Taken during the workshop, at the entry to the LPI*

Recommendations: Next Spectral Data Set

On June 10 - 11, 1999 the workshop "Spectroscopy of the Martian Surface: What Next?" was held at the Lunar and Planetary Institute in Houston, TX. At this workshop, leaders of the science community with expertise in spectroscopy and remote mineral identification met to discuss the state of understanding of Mars surface composition, and to assess what critical gaps may exist after the successful completion of currently planned Mars missions. Participants agreed that the most critical gap that will remain is a spectral data set containing targeted, very high information content measurements to support the selection of landing sites that may preserve biomarkers. This letter summarizes the consensus of the participants.

Should the currently planned instruments complete their objectives, then we feel that the global reconnaissance mapping of Mars will be completed. The Global Surveyor TES will provide global measurements of Mars using emission spectroscopy (6 - 50 μm) at 3 km spatial resolution. This will be complemented in 2001 by multispectral visible and thermal infrared imaging at <100 m/pixel (MARCI and THEMIS), and in 2003 by hyperspectral visible and near-infrared imaging (0.4 to 5.0 μm) at 2 km/pixel (Mars Express OMEGA).

The next instrument should measure spectra of targeted regions to support lander site selection. Mineralogy is an essential tool to assess ancient and modern environments on Mars that may have been conducive to the support and preservation of life and biomarkers. Reflectance and emission spectroscopy remain the most capable method for remote mineral identification. It is likely that the global data sets (TES, THEMIS, MARCI, OMEGA) can be

used to identify many potential sites for lander science measurements and sample return. Experience gained from spectral data sets of Mars and Earth has shown that an unambiguous interpretation of a complex region requires spectra with both high spatial resolution and very high information content. Selecting the most desirable landing site will require this type of data set. High information content is obtained by measuring with broad spectral range, high spectral resolution, and most importantly high signal to noise ratio. The data set should not be global, but should focus on the most promising sites identified from the global data sets. The proposed Ariane piggyback micromissions will lack the payload for an instrument capable of making these measurements.

Neither reflectance nor emission spectroscopy alone is sufficient to uniquely determine the full range of minerals that may be present, as each method is sensitive to different physical processes. Together they provide the best capability to identify the surface mineralogy. The broader the spectral range, the less ambiguous the interpretations, and the more technical the justification for selecting a particular landing site.

Interpretation of current and planned data sets will require access by the community to spectral libraries that contain measurements of materials of interest over the full wavelength range of the spacecraft instruments (0.4 - 50 μm). To facilitate site selection, spectral libraries should be expanded and made available to the community.

On the basis of our extensive experience with laboratory, planetary, and terrestrial spectroscopy, the workshop participants identified the following instrument characteristics required to best select among potential landing sites:

Such an instrument would provide an essential tool in the phased approach to Mars exploration that NASA has developed. We strongly encourage NASA and the Mars community to consider these recommendations in planning for future missions.

Sincerely,

Participants of the workshop, "*Spectroscopy of the Martian Surface: What Next?*"

Jim Bell
Ben Clark
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Allan Treiman

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Scott Murchie
John Salisbury
Steve Young

Phil Christensen
Stéphane Erard
Rudy Hanel
Eric Keim
Paul Lucey
John Mustard
Steve Saunders

Recommendations: Supporting Research

Summary Recommendations: Spectroscopic remote sensing of surface composition has been of critical importance to our current understanding of Mars, as well as other planets. Spectroscopy, especially high resolution spectroscopy, will continue to be of great importance for future Mars exploration and is particularly important for assessing present and past environments in the search for evidence of life. There are two areas that need more emphasis by Research and Analysis Programs: 1) Measurement and public archiving of spectra covering the range 0.4 - 50 μm ; and 2) Testing of quantitative mineral analysis methods. Participants also felt there should be additional discussion of what materials should be measured, and how the data should be archived.

Background. On June 10 - 11, 1999 the workshop "*Spectroscopy of the Martian Surface: What Next?*" was held at the Lunar and Planetary Institute in Houston, TX. At this workshop, leaders of the planetary community with expertise in spectroscopy and remote mineral identification met to discuss the state of understanding of Mars surface composition, and to assess what critical gaps may exist in planned measurements of Mars and supporting research programs. This letter summarizes our consensus about the supporting research programs.

Knowledge of surface composition is an essential tool to assess ancient and modern environments on Mars that may have been conducive to the support and preservation of life and biomarkers. Reflectance and emission spectroscopy are the most capable method for remote compositional mapping. Participants concluded that there remain several critical needs in the ability of the community in order to reliably interpret current and planned spectral data sets. One is the unavailability of supporting spectral libraries that contain diverse measurements over the entire wavelength range measured by current and planned spectrometers (0.4 - 50 μm). Another is the need to test and compare currently available analytical methods that are used to quantitatively examine remotely sensed spectra.

Laboratory spectra. Two factors are essential for detection and quantification of surface materials: high information content spectra of Mars, and high quality laboratory spectra. Participants concluded that a lack of access by the entire community to measurements over the full wavelength range measured by current and planned spectrometers (0.4 - 50 μm) seriously impedes interpretations. Measurement of diverse materials relevant to active processes and the environment of Mars over the full wavelength range should be encouraged by current Research and Analysis Programs. This community effort will be strongly aided by insuring that there is a community measurement facility capable of measuring the entire 0.4 - 50 μm range. It is essential to the success of this integrated approach that spectral data measured under this program are publicly archived, and that the materials measured are well-characterized.

Quantitative methods. Workshop participants concluded that there is a strong need to test and evaluate currently available identification and unmixing algorithms. An important baseline could be established through blind measurements by different algorithm proponents of prepared samples representing increasing degrees of difficulty.

Participants also felt quantitative methods will be advanced by the development of liaisons to similar research programs, such as those developed by Department of Defense and Intelligence agencies. One goal should be to test and incorporate knowledge from these other programs into the NASA community, perhaps by inviting them to participate in the blind measurement program.

Additional discussions. Participants concluded there should be additional public discussion of what materials should be measured, and how the data should be archived. Materials discussed included weathering materials and coatings, and poorly crystalline materials that may be present on Mars. The workshop did not have the goal of addressing these issues, and no consensus was reached, but these issues were felt to be of sufficient importance to warrant further discussion.

Recommendations. Selecting among potential landing sites will be aided by measuring targeted, high information content spectra from orbit, followed by clear, unambiguous interpretations of the spectra. Community access to measurements over the full wavelength range covered by current and planned instruments, and the development and testing of quantitative analysis methods will provide the enabling foundation and data analysis tools that are essential to the phased approach to Mars exploration that NASA has developed. We strongly encourage NASA and the Mars community to consider these recommendations in planning for future research programs.

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Kenneth Herr
Melissa Lane
John Mustard
Steve Saunders

Eric Keim
Paul Lucey
Carlé Pieters
Allan Treiman

Laurel Kirkland
Scott Murchie
John Salisbury
Steve Young

Recommendations: Mars Airplane

Participants felt that with the successful completion of the currently planned remote sensing instruments (TES on Mars Global Surveyor, THEMIS on Mars '01, and OMEGA on Mars Express '03), the next step for Mars surface spectroscopy is targeted imaging spectroscopy at spatial scales < 100 m.

Participants recognized that the Mars Airplane could act as a science and technology demonstration mission, paving the way for the next generation of observation, provided an appropriate instrument was flown at a good location. This instrument would need to have spatial resolution of a few 10's of meters. The instrument should cover a wavelength range at sufficient spectral resolution ($\lambda / \lambda \Delta > 250$) and signal to noise ratio (>500) to be able to identify specific diagnostic mineral spectral features. High spectral resolution is needed for definitive mineralogic characterization, because the currently planned global survey products will likely be sufficient to identify candidate locations that may contain mineral deposits conducive to preservation of a fossil record. However, a data product capable of prioritizing and characterizing in more detail an interesting site at higher spatial and spectral resolution than is currently planned is of high interest to the community.

While imaging spectroscopy is desirable, a profiling spectrometer taking spectra along the airplane track would also return scientifically useful data, provided it was registered to images. However, a poorly chosen instrument or one flown to a location where the geologic setting would not predict mineralogical variations could be a serious setback in the overall goal of exploring Martian mineralogy at these spatial scales.

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Workshop Program

* = presenter

Thursday, June 10, 1999

7:45 Registration
8:15 Welcome, Introductory remarks

PRESENTATIONS I
8:30 a.m.
Chair: Carlé Pieters

Format: Each talk is 15-20 minutes, followed by a 15-10 minute discussion/questions period.

Mars program + sample return

8:30 Steve Saunders*, Spectroscopy for Mars Exploration

9:00 Jack Farmer*, Environmental and Mineralogical Controls on Fossilization: Key Elements in a Strategy for Mars Exopaleontology

Past/Current data sets

9:30 Jim Bell*, Fifty Years Of Mars Surface and Atmospheric Composition from Telescopes: Highlights and Implications For Spacecraft Studies

10:00 Ken Herr*, 1969 Mariner Mars Infrared Spectrometer (IRS): Lessons for Future Exploration

10:30 BREAK

10:45 Rudy Hanel*, 1971 Mariner Mars Infrared Interferometer Spectrometer (IRIS)

11:15 John Mustard*, Review of the 1989 ISM Instrument and Results

11:45 Phil Christensen*, Mars Surface Mineralogy and Petrology from 1997 MGS TES Data

LUNCH

12:15

PRESENTATIONS II

1:30 p.m.

Chair: John Salisbury

Format: 15 minute talk + 10 minute questions/discussion. The combined Mini-TES/THEMIS talk is 25 minutes +15 for questions/discussion.

Planned and terrestrial data sets

1:40 Carlé Pieters*, J. F. Mustard, and S. L. Murchie, Aladdin Instruments at Mars

2:05 Phil Christensen*, Overview of the Mini-TES and THEMIS Instruments for the Mars 2001 Surveyor Mission

2:45 Paul Lucey*, A Strategy for Future Mars Spectral Remote Sensing: An Outsider's Opinion

3:10 BREAK

MODERATED PANEL DISCUSSION

3:25 p.m.

Moderator: John Mustard

Format: Each panelist has a 10 minute talk, and 5 minute questions/discussion. Followed by 60 minute discussion.

3:25 Visible/Near-IR: Roger Clark

3:40 Thermal IR: Phil Christensen

3:55 Both: Jack Salisbury

4:10 "Outside the community" spectroscopist: Paul Lucey

4:25 Surface studies: Ben Clark

4:40 Discussion (60 minutes)

GROUP DINNER

6:30

The Italian Café

Friday, June 10, 1999

PRESENTATIONS III

8:15 a.m.

Chair: Allan Treiman

Format: 15 minute talk, then 10 minute discussion/questions.

8:15 Introductory remarks.

8:25 Diana Blaney* and D. Glenar, In Situ Spectrometers for Martian Mineralogy

8:50 Roger Clark* Mapping the Surface Mineralogy of Hydrothermal Alteration Systems:
Applications to the Geologic History of Mars and the Search for Past Life

9:15 William Farrand*, Sub-pixel Detection and Mapping of Spectrally Unique Materials on Mars
using ISM Data

9:40 Gary Hansen*, Remote Sensing Spectroscopy of the Polar Regions of Mars

10:05 BREAK

10:20 Eric Keim*, The SEBASS Hyperspectral Imaging Spectrograph: Instrument Description and
Sample Thermal Images Obtained Near Flagstaff, Arizona and Mesquite, Nevada (15 minutes + 5
for questions)

10:40 Steve Young*, Use of Thermal Hyperspectral Imagery in Terrestrial Surface Characterization
(15 minutes + 5 for questions)

LUNCH (brought in)
11:00

WORKSHOP REPORT MODERATED DISCUSSION

11:45 p.m.

Moderator: Paul Lucey

11:45 Discussion

The discussion will begin with any major issues left unresolved from the panel discussion, and then will address submitted questions.

ADJOURN

2:45

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FIFTY YEARS OF MARS SURFACE AND ATMOSPHERIC COMPOSITION FROM TELESCOPES: HIGHLIGHTS AND IMPLICATIONS FOR SPACECRAFT STUDIES

J. Bell, Cornell University, Ithaca, NY, <jimbo@marswatch.tn.cornell.edu>.

The modern era of Mars telescopic studies began shortly after World War II, with Gerard Kuiper's spectroscopic discovery of CO₂ in the Martian atmosphere. Other early studies included measurements of Martian water vapor, searches for infrared spectral features from organics, discovery of hydrated mineral absorption features in the near-infrared, and characterization of the detailed visible-wavelength spectral reflectance properties of the surface materials. Improvements in telescopes and detectors over the years have yielded associated improvements in spatial and spectral range, resolution, and SNR. This talk will review a number of important findings that have come from these studies, including both atmospheric composition and surface mineralogy. Also discussed will be more recent findings and controversies, especially on surface mineralogy, that have come from even higher spectral resolution near-IR telescopic observations and higher spatial resolution HST observations.

A common theme among the telescopic observations is that increased spatial resolution provides for increased spectral heterogeneity. On broad regional scales, spectral variability is muted by the presence of fine-grained and relatively spectrally-bland surface and airborne dust. On finer spatial scales, however, telescopic observations can "see through" this dust in small areas (tens to hundreds of km) where local bedrock or local soil deposits are visible, and detect more spectral diversity. The fact that even from Earth telescopic observations can detect subtle variations in ferric oxide, pyroxene, and hydrated mineral absorption features bodes well for future visible and near-IR

spacecraft global spectroscopic investigations like MARCI (this optimism is borne out in part by the evidence for spectral variability seen even in the poorly-spectrally-sampled Viking Orbiter color imaging data and the small and spatially-limited Phobos-2 ISM dataset).

There have been many fewer infrared telescopic studies of Mars, but even these have been able to detect some spectral variability, especially when imaging at high spatial resolution. This bodes well for future (current) high spatial resolution spacecraft infrared studies like MGS/TES, which will hopefully detect much more infrared spectral variability during its systematic mapping mission. Fewer specific minerals have been identified or proposed based on infrared telescopic observations compared to visible and near-IR observations, however, and this represents a challenge for infrared instruments. While there is great potential to detect a number of important primary and secondary mineral phases from infrared observations, extracting this unique information from a complex emissivity signature that includes the atmosphere and surface dust/coatings over a range of temperatures is not straightforward. Many of the same problems are encountered at the shorter reflected light wavelengths, of course, but relatively mature surface and atmospheric radiative transfer modeling has allowed purely surface constituents to be identified. It will be interesting to see in the coming year if TES is able to also uniquely identify many different surface mineralogic constituents through similar modeling efforts.

The history of modern telescopic observations has revealed that spectral

TELESCOPIC SPECTROSCOPY OF MARSJ. Bell

diversity exists on Mars at fine spatial scales, and that both visible/near-IR and IR techniques can detect this variability. Ultimately, there is little value in debating whether reflectance observations or emissivity observations are "best", because both offer advantages for different types of surface studies. Just as it has been important to seek the truth about Martian surface and atmospheric composition using both reflectance and emissivity techniques from telescopic observations, it will be important to measure both of these spectral domains from spacecraft in Martian orbit. TES provides the first opportunity for global

mapping spectroscopic observations in the infrared, to be followed up by higher spatial resolution IR imaging from THEMIS. Hopefully a similar opportunity for high spatial resolution visible/near-IR spectroscopy will become available (perhaps OMEGA?) to complement the high spatial resolution visible/near-IR imaging studies to be performed next year by MARCI. The combination of global measurements across the entire spectral domain will ultimately strengthen our ability to interpret the observations in terms of unique surface mineralogic components.

SUB-PIXEL DETECTION AND MAPPING OF SPECTRALLY UNIQUE MATERIALS ON MARS USING ISM DATA William H. Farrand, Space Science Institute, 1540 30th, #23, Boulder, CO 80303 (farrand@rmi.net)

Introduction: One of the primary goals in the exploration of Mars is the location of geologic deposits formed by, or associated with, liquid water. These types of deposits would include hot spring formed materials (silica and calcic sinters), cold spring formed materials (ferricretes, tufas, travertines), evaporites, carbonates, and mineral deposits formed by hydrothermal activity (containing sulfides, and sulfide alteration products). Many of these deposits, in particular spring-formed deposits, are spatially restricted in area. In fact, the ground instantaneous field of view (GIFOV) of current and planned Mars orbital multi- and hyperspectral sensors is greater than many of these types of deposits. Hence, in order to find these types of deposits using existing and planned sensors, sub-pixel detection techniques will be necessary. A number of techniques that can detect materials at spatial coverages of less than 10% of a pixel have been developed for terrestrial airborne multi- and hyperspectral sensors [1-3]. These techniques can be applied against Mars multi- or hyperspectral data sets to very good effect. Anomalous pixels mapped with sub-pixel detection methods can be located on higher resolution panchromatic (Viking Orbiter or MGC MOC) imagery. In this paper the applicability of one of these techniques, Foreground / Background Analysis (FBA) [4] will be tested against ISM data from the Phobos 2 mission [5].

Technique: FBA is very similar to Spectral Mixture Analysis [6], but differs in its implementation and also in its results. While SMA results in a fractional abundance image for each spectral endmember, FBA distinguishes the endmembers into one or more which constitute the "foreground" and the remainder which constitute the "background". A vector of weights is calculated which when applied against a pixel covered entirely with the foreground/target material will return a data number (DN) of 1.0

and when applied against a pixel devoid of the target material will return a DN of 0. The vector of weights, w , is determined by means of a singular value decomposition and solving for a weighted matrix of endmember spectra.

Example: ISM data were examined using SMA and FBA. An example is presented using ISM data over the Melas and Coprates Chasmata. The atmospherically corrected ISM data were provided to the author by Dr. Stéphane Erard. The data for the "aur" ISM "window" (whose location is shown in Figure 1) were analyzed by standard SMA in order to determine three primary endmembers: dust/bright area deposits, basalts, and an undetermined intermediate albedo material. A fourth less abundant, but spectrally unique material was also determined. FBA was applied to the data using this fourth material and the resulting abundance image is shown in Figure 2. The spatial pattern displayed by high abundances corresponds to the northern wall of Coprates and Melas Chasmata. Geometric registration of the highest value FBA pixels to a Viking base image is shown in Figure 1; the highest values correspond to areas of slumping in the canyon wall. The spectrum of the target material is shown in Figure 3a and a profile across the FBA abundance image in Figure 3b shows the accentuation of the target material and the successful suppression of the background.

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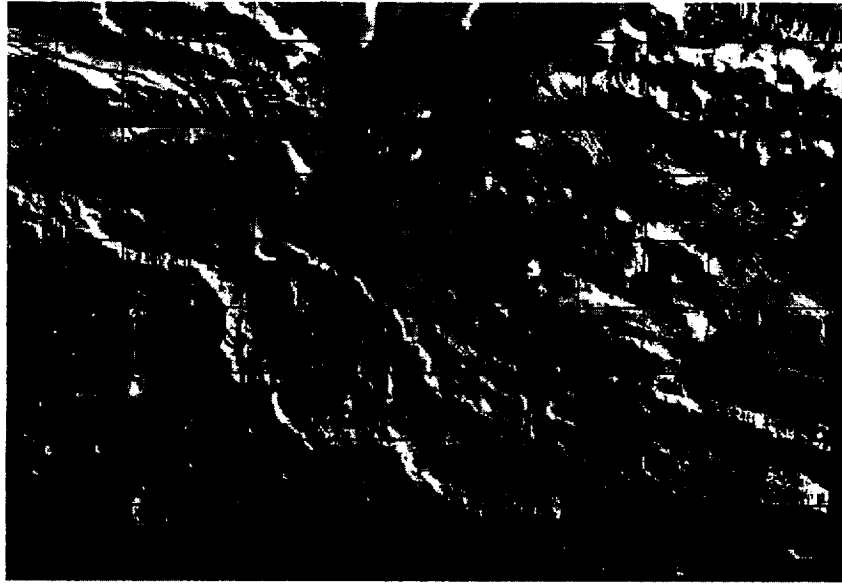


Figure 1: Viking orbiter base image over Melas Chasma and western Coprates Chasma. The box outlines the approximate borders of the “aur” ISM window. The circles indicate the approximate centers of the highest value pixels in the FBA “wall rock” abundance image.



Figure 2: FBA abundance image of “wall rock” endmember. The highest value pixels in this figure correspond to the circles in Fig. 1.

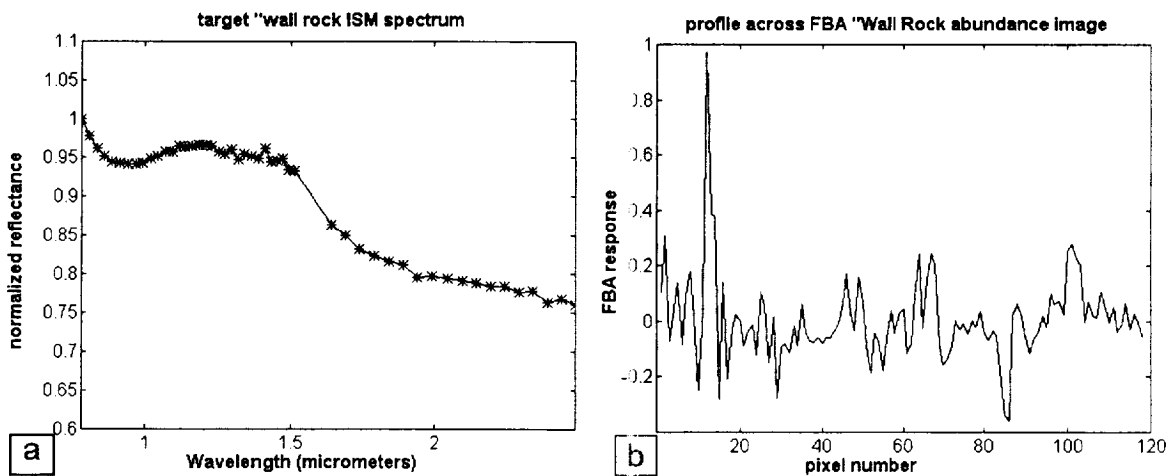


Figure 3: (a) 50 channel spectrum (from the ISM “even” channels) of the “wall rock” endmember. (b) Profile across FBA “wall rock” abundance image.

Environmental and Mineralogical Controls on Fossilization: Key Elements in a Strategy for Mars Exopaleontology. J. D. Farmer, Arizona State University <jack.farmer@asu.edu>.

(Submitted to Fifth International Conference on Mars)

Introduction: One cannot expect to land just anywhere on Mars and discover a fossil record. What are the important factors that should guide the search? While the potential range of fossil information preserved in rocks of all ages is quite broad, including actual cellular remains (1), various classes of chemofossils (2), biominerals, biofabrics, and stromatolites (3), studies of fossilization processes in modern environments on Earth, as well as the terrestrial fossil record, indicate that the preservation of biosignatures is strongly influenced by the physical, chemical and biological factors of the environment (4). Acting together, these factors determine the types of deposits and range of information preserved.

Important Fossilization Processes: On Earth virtually all of the well-preserved cellular microbios in the Precambrian were preserved by either 1) early diagenetic infusion of silica or phosphate into organic materials and sediments, or 2) by rapid burial of organic materials in fine-grained, clay-rich shales. These two situations comprise a very narrow taphonomic window that greatly restricts opportunities for preserving cellular level biosignatures in rocks (4). Of course, there are also intrinsic properties of organisms that promote their preservation, such as the presence of recalcitrant cell walls or extracellular elements. While fossilization requires very special conditions, still we have documented an extensive Precambrian fossil record on Earth. It is crucial that such preservational constraints be considered carefully before mounting an expensive and time-consuming campaign to explore for an ancient Martian biosphere. Environments where the sedimentary processes defined above commonly operate in the presence of biology include: arid marine or lacustrine shorelines (5), evaporite basins (6), mineralizing springs (7), and subsoil hardpans (8).

Long-term Preservation: Rock type (e.g. the mineralogy and texture of the host sediment) is also a fundamental factor influencing the long-

term preservation of biosignatures. In this context, most important is the rapid reduction of permeability following sedimentation and burial. This typically follows the compaction of fine-grained sediments, along with secondary mineralization (cementation). The reduction of permeability during early diagenesis serves to isolate and protect organic remains from later oxidation. A second critical factor is the microstructural and chemical stability of the enclosing sedimentary matrix. This promotes long-term retention of biofabric and chemofossil information which may remain even when organic materials have been lost. Long-term microstructural and chemical stability to a large extent depends on mineralogy.

While the best preservation of fossil information is typically in sedimentary silica or phosphate, most of the Precambrian fossil record on Earth is actually hosted in carbonates (primarily as stromatolites). These provide primary mineralogical targets in the search for fossil record on Mars. However, the tendency of carbonate minerals to undergo recrystallization during diagenesis often leads to the loss of important microstructural details.

Crustal Residence Time: Evaporite minerals provide another potential target for a Martian fossil record (9). During precipitation from supersaturated brines, terrestrial evaporites typically capture numerous halophilic microorganisms present as biofilms on accreting mineral surfaces, or within fluid inclusions. However, where an active hydrological system is present, evaporites are easily dissolved and lost from the rock record. Hence, evaporites are quite rare in ancient sequences on Earth. The same may not hold true on Mars where the hydrological cycle has been far less active.

Ice provides another potential target for a fossil record (10). However, by geological standards, the crustal residence time is exceedingly short for ice. Although ice provides an excellent medium for preserving organic

materials (11), it tends to be easily lost from the crust during cycles of climatic warming (12). This suggests that on Mars, ground ice is likely to be unimportant as a target for exopaleontology, with the exception of situations where subsurface aquifers have recently replenished the near surface cryosphere. In that case, upflowing ground water may have carried representatives of an extant subsurface biota into the near-surface environment, cryopreserving their remains in ice.

Conclusions: Observations drawn from terrestrial paleontology comprise crucial elements in the present strategy to explore for a fossil record on Mars. In the most detailed sense, the strategy has yet to be applied. At the bottom line, successful application to the problem of site selection will involve more than just identifying

sites where water was present. There are many sites on Earth where water is abundant but fossils rare or absent. In selecting landing sites on Mars we must be able to take the strategy to the next level of application by asking crucial questions about the early diagenetic mineralization, and the other factors of the sedimentary systems that are required for microbial fossilization. From an exploration standpoint, the first step in the process is to identify and locate the right kinds of deposits. Mineralogy provides the most reliable information for properly assessing the potential for capturing and preserving of a fossil record. In meeting this important requirement, high spatial resolution mineralogical mapping should be given the highest priority in future missions (13).

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Introduction. ISM was the imaging spectrometer of the Phobos-2 mission, the first space-borne instrument of this type to return scientific data from the planets. The instrument was developed by IAS and DESPA in France, with support from CNES. Between January and March 1989, it returned ~80Mbit of data consisting mainly in 9 medium resolution (25km) and 2 high-resolution (7km) image cubes of Mars. All observations were performed in the equatorial regions, and span the 0.73-3.15 μm domain in 128 spectral channels. ISM also acquired one image cube of Phobos at 700m resolution, and various limb observations of Mars. Although the spectral resolution of ISM is comparable to that of previous ground-based observations, its angular resolution (12'x12') and signal-to-noise ratio (up to 1500) are much better than those of any other spectral measurement on Mars, and remain unchallenged in this spectral range.

The public release of the PDS-formatted data set is expected in 1999 (CNES Planetary data base). A preliminary version of the archive, including calibrated and derived data, has been widely distributed for several years directly by IAS. Information can be found at:

<http://www.ias.fr/cdp/ISM/welcome.html>

Instrument principle. The dispersive system is a grating, the first two orders of which are separated by a beam-splitter and focused onto two PbS arrays. Each array consists of two rows of 32 detectors, looking in directions that differ by ~23'. A complete spectrum is acquired at each time step. The image format of the data results from both the orbital motion of the spacecraft and the scanning motion of an entrance mirror. The integration time (ranging from 0.125 to 1 s) is selected to get a limited drift during acquisition, and depends mainly on spacecraft altitude. The number of pixels per line is then selected to get a one-pixel shift between two lines, and an analog gain is used to optimize the signal to noise ratio.

The limiting steps in the calibration process are the correction of spectral orders overlap (due to imperfect transmission of the beam-splitter), focal plane temperature variations, and transfer function. Channel-to-channel relative accuracy is comparable to that of the most accurate telescopic spectra, typically 3-5%. However, the real limit of data analysis is imposed by the signal to noise ratio, on the order of 0.3% in most of the spectral range (~3% above 2.8 μm).

Atmospheric studies. Gaseous absorptions were used 1) to study surface topography (using CO₂ bands), and 2) to study minor atmospheric species (CO, H₂O).

Topography was measured by fitting the profile of the 2.0 CO₂ band of ratioed spectra with a ratio a

synthetic spectra computed with the semi-empirical band model of [1], the GEISA library, surface pressures and a temperature profile from Viking [2, 3]. The relative accuracy was estimated between 100 and 300 m, depending on altimetry. Therefore this method provides better results than stereophotogrammetry in regions with slow topographic variations (on the order of 1 km). The absolute accuracy however is limited to 700 to 2000 m. The data base contains a topographic map of all regions observed at a resolution of 0.3° in longitude and latitude. The largest difference with Viking topographic map is observed between the western and eastern sides of Olympus Mons (ISM altitudes differ by ~2 km, while Viking altitudes are similar). The discrepancy could result from the inherent cumulative error of the stereophotogrammetric method.

The most accurate results concerning H₂O and CO distributions were published by [4]. The average water content is ~11 pr- μm , with diurnal and latitudinal variations globally consistent with Viking MAWD observations in 1976-79 [5]. The average value is larger than that observed by Viking (~8 pr- μm in similar conditions), but agrees with telescopic data of 1988 of [6]. Variations of water vapor with altitude show an excess of water vapor atop the volcanoes. Two mechanisms were proposed to explain the difference in water exchange between the volcanoes and the surrounding plateaus ([7] [8]): the first one implies a difference of adsorptive properties (clays on the volcanoes, basalt on the plateau); the second one relies on the difference of thermal properties (relatively low albedo and very low thermal inertia on the volcanoes, resulting in higher noon temperatures).

Studies of CO by [4, 7] showed an apparent inconsistency over the volcanoes between ISM observations and Earth-based estimates of the CO / CO₂ mixing ratio. If surface properties (composition, grain size...) are constant with altitude, CO may be constantly depleted above the volcanoes. A possible mechanism is related to CO trapping by aerosols: laboratory measurements by [9] suggest that CO mostly recombines on the airborne dust below an altitude that depends on the dust optical depth; this relationship would be complicated by the coupling between dust vertical distribution and surface elevation. Therefore heterogeneous processes could contribute to the CO depletion, that would be somehow correlated to concentrations of airborne dust. However, these measurements are sensitive to instrumental artifact, and higher spectral resolution measurements are required.

Aerosols. Spectra of aerosols were derived by [10] and [11]. The first attempt permitted to estimate particles distribution, and yielded an effective radius

$r_{\text{eff}} \sim 1.25 \mu\text{m}$. This particle size is only half of that measured by Mariner 9 ($r_{\text{eff}} \sim 2.75 \mu\text{m}$, [12]) and the distribution is twice as narrow ($v_{\text{eff}} = 0.25$ versus 0.418), but this result agrees with those of Auguste, KRFM and Termoskan on board Phobos-2, although there seems to be a rather large uncertainty on the width of the distribution [13].

[11] applied the same model to areas that were observed twice under different viewing geometries. The scattering continuum derived agrees with that of [10] and with optical parameters derived from Viking IRTM ($w \sim 0.9$, $g \sim 0.6$, [14]). In addition, continuum-ratioed spectra allowed analysis of aerosols absorptions up to $2.5 \mu\text{m}$. Most of them were ascribed to H_2O ice, except a small absorption at $1.8 \mu\text{m}$ observed only in some hydrated clay minerals and in gypsum, but in no other usual Martian analog material. [11] also found that the vertical aerosols opacity is largely independent of surface elevation. This result is consistent with an observation of Olympus Mons by IRTM, showing an increasing dust-to- CO_2 mixing ratio above 10 km elevation ([14]). Such a vertical structure, consistent with that inferred from Viking by [15], could bear some relationship with the CO distribution discussed above, would CO recombination be catalyzed by airborne dust or ice crystals.

A major conclusion concerns the effect of aerosols scattering on observation of the surface. The contribution to the overall signal is very large (up to 25% of the reflected light at $1 \mu\text{m}$, consistently with estimates from IRTM [14]), and deeply modifies the apparent surface absorptions (negative spectral slope, reduced contrast, and shift to longer wavelengths).

Surface features. The main signatures of surface materials have been discussed by [16]. Apart from albedo and spectral slope, they consist in hydration band at $2.7\text{--}3.15 \mu\text{m}$ and Fe-related absorptions at $0.8\text{--}1$ and $2.2 \mu\text{m}$. More subtle features have been identified in limited areas. The very high signal to noise and the imaging capacity make it possible to

interpret spatial variations at the level of $\sim 0.5\%$.

Variations in spectral slope have been studied extensively by [17], who ascribe them to ferric coatings of variable thickness in some areas (in particular on the flanks of Olympus Mons). The $3 \mu\text{m}$ H_2O band depth was found to be highly correlated to reflectance. In bright regions, it corresponds to a weight fraction of $\sim 2\%$ water [18].

Bright region have characteristics of hydrated, poorly crystalline, iron oxides. Subtle local variations indicate that some bright materials are not remobilized and mixed. Most of these variations are ascribed to differences in particle size or degree of crystallization, but some small areas could have high concentrations of other alteration materials, phyllosilicates or sulfates [19].

Dark areas have been studied specifically by [20–22]. Fresh dark materials of various ages were interpreted as two pyroxenes basalts, with spectral characteristics close to the basaltic SNCs (Shergotty, Zagami...). This suggests that SNCs are relevant to large regions of Mars and large periods of time. In older areas, these materials have been interpreted as komatiites, warm and fluid lavas formed deep in the mantle [23].

Other, “anomalous”, materials are observed. In particular, an unusual material found in the layered deposits of Valles Marineris, with both mafic and hydration characteristics, suggests that hydrovolcanism was an important factor in the development of this area [24, 25]. A possible signature of carbonates was observed in Lunae Planum, an old dark area [26].

ISM data were also used to build composite spectra in the $0.4\text{--}5.7 \mu\text{m}$ domain, together with telescopic spectra and IRS observations of the same regions [27]. These composites are currently used in a spectral model of Mars to prepare future observations by OMEGA on-board Mars-Express.

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OMEGA, the imaging spectrometer on board Mars-Express.

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Introduction. OMEGA is a second generation instrument developed after ISM/Phobos-2. OMEGA was originally developed for the Mars-96 mission by IAS and DESPA in France, IFSI in Italy and IKI in Moscow. OMEGA spare unit has been selected to fly on board the Mars Express ESA mission, planned to launch in 2003. The main differences with ISM performances include extended spectral range at both shorter and longer wavelengths (0.5-5.2 μm), and increased angular and spectral resolutions. The instrument is made up of two co-aligned channels (visible and NIR), each using a dedicated telescope and foreoptics.

Visible channel. The visible channel works in pushbroom mode, using a Thomson CCD matrix 384 x 288 pixels (spatial x spectral). The total field of view is 8.8°. In baseline modes, pixels are binned either 3x3 or 3x2, providing a spatial sampling (IFOV) of 4.1 arcmin and a spectral sampling of 7 nm and 4 nm respectively: the beam is spread through an holographic grating over the spectral range 0.5-1.1 μm , over 96 or 144 "spectels".

Infrared channel. The NIR channel works in whiskbroom mode, with an IFOV of 4.1 arcmin. The incoming radiation is divided in two subchannels, each using a grating spectrometer working in the first order. A crosstrack scanning mechanism is used to build swaths of 16, 32, 64 or 128 IFOV width, depending on the spacecraft altitude.

The two subchannels operate in the ranges 1.0-2.7 μm and 2.6-5.2 μm with a spectral resolution of 13 and 20 nm respectively. The detectors consist in linear arrays of 128 InSb detectors, cooled down to 70K, each by a dedicated cryocooler. The two spectrometers are cooled down to 190K by a passive radiator.

The measured signal to noise ratio is higher than 100 over the entire spectral range, and exceeds 300, at 5 ms integration time, with no summing, over half the spectral range.

Operating modes. For OMEGA, the major goals are to perform a global coverage of the surface, with a spatial resolution < 5 km, and to cover a fraction of the surface at high resolution (< 500 m). This is achieved in operating at different altitudes, and thus with different operation parameters. 8 sampling modes are available, both for the visible and the IR channels. These modes consist in combinations of integration times, swath widths in the NIR channels, and binning modes, adapted to different orbital configurations. Integration times vary from 2.5 to 20 ms (nominal 5 ms). The main two modes are adapted to global mapping from altitudes 1500 to 4000 km, and to high resolution snapshots from low altitude (pericenter).

From orbit pericenter (altitude < 300 km), the resolution reaches 400 m. The NIR channel acquires swaths 16 pixels large (~8 km) and 1500 km long. The 16 pixels swaths are scanned in 100 ms, corresponding to a drift of ~400 m, thus leading to contiguous swaths along the track.

For global mapping, typical sessions will have swaths of 128 pixels large (500 km) and 3000 km in length.

On-board signal processing. An on board compression unit, wavelet based, allows compression expected to reduce the downlink data by a factor 3 to 10, therefore permitting longer observation sessions in the allocated memory. Typical sessions of 200 Mbits last 400 s close to pericenter, up to 20 min from higher altitudes.

Scientific observations. The spectral range used gives access to spectral features of major (CO_2) and minor (H_2O , CO) atmospheric species, aerosols (suspended dust and ices), and surface minerals.

CO_2 absorptions will provide on each resolved pixel the altimetric determination, in a way similar to Mariner 9 and ISM. Water vapor and CO absorptions will permit monitoring of minor species with location, altitude and time, at both diurnal and seasonal scales, linked to the atmospheric photochemistry processes.

The 1-2.5 μm range is sensitive to aerosols scattering. Overlapping spatial observations will therefore permit to estimate aerosols size distribution, again at different locations and times.

Both H_2O and CO_2 ices have typical spectral features in the 1-5.2 μm range that will make possible the study of ice clouds distribution.

Surface minerals have characteristic features at 1 and 2 μm (pyroxenes, oxides) indicative of mineral abundance once the aerosols scattered contribution is removed from the signal. Salts (carbonates, sulfates, nitrates...) and alteration minerals (oxides, phyllosilicates...) have subdued features in particular at 2.3 μm and between 3 and 5 μm , that can be studied with the instrument signal to noise ratio.

This is an abstract from the workshop, "*Spectroscopy of the Martian Surface: What Next?*", held at the Lunar and Planetary Institute, Houston. More information is available [here](#).

[Laurel Kirkland's home page](#)

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1971 MARINER MARS INTERFEROMETER SPECTROMETER (IRIS). A. Hanel,
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The success of identifying a mineral (Quartz) in the desert areas on Earth by an IRIS on the meteorological spacecraft Nimbus had raised our hope to do the same on Mars. However, as Mariner 9 arrived at Mars, a global dust storm was near its peak. The whole planet was engulfed by a dust cloud. The Martian spectra, although covering a wider spectral range than the Nimbus spectra, showed signatures of CO₂, water vapor and a wide, but relatively smooth feature of the dust suspended in the atmosphere. This feature appeared in emission in the south-polar and in absorption in the mid-latitude spectra. In the beginning, it was not even clear in what spectral range and to what extent emission from the surface emerged.

The dust features did not resemble the familiar quartz characteristic, nor that of any of the laboratory spectra of powdered minerals available to us. At that time, all we could say was that the feature had a broad maximum at about 1100 cm⁻¹. Available mineral spectra showed a general pattern of shifting the absorption maxima towards higher wavenumbers with increasing silicon content. Using this relationship, we concluded that the silicon content of the dust cloud was relatively high (about 60%). This indicated that Mars had differentiated into a core and a mantle. Before that time, this was not known.

The absence of sharp features in the dust spectrum indicated also the likelihood that several minerals were involved, each one filling transmission gaps of the others. Subsequently, many suggestions were made concerning the dust composition, but none seems to fit the data very well. The ideal solution would require the application of the Mie-Theory, but, as far as I know, this has not

yet been accomplished. The main reason is probably the lack of information on the complex refractive index as a function of wavenumber for many possible candidates for the dust.

As time progressed, the atmospheric dust settled more and more to the ground and the surface was exposed, although it remained unclear to what degree residual dust still was in the atmosphere and to what degree the dust now on the surface obscured genuine mineral signatures. The spectra taken late in the life of Mariner 9 resembled more and more the shape of a blackbody. Strong emissivity signatures have not been apparent. The relatively large field of view of IRIS, combined with the highly elliptical orbit of Mariner 9, resulted in spectra averaging over large areas, often several thousand square kilometers. This may have further reduced the chance of seeing pronounced emissivity features.

An exception to this is the appearance of a hematite feature, first seen by TES, but also found later in IRIS spectra. This shows that further examination of the IRIS spectra, specifically of those in the latter part of the mission, may still be worthwhile.

A south polar-spectrum showed a mixture of dark and bright areas. Ignoring the gaseous CO₂ and water bands as well as the dust signature, one could fit the spectrum well with a superposition of two blackbodies, one with a temperature of about 140 K and a second one with 235 K. The relative strength of the blackbody spectra was in agreement with the areas of bright and dark surfaces observed simultaneously by the Imaging System for the IRIS field of view, suggesting the colder surface to be CO₂ ice and the warmer exposed soil after the ice had

evaporated. This was clear evidence that the south-polar cap was CO₂ and not water ice. Spectra of the north-polar cap led to the same conclusion.

IRIS also identified the so called W-cloud to be water ice. Vertical profiles of atmospheric temperatures lead to east-west

profiles of wind speed, indicating a strong circumpolar jet in the southern hemisphere. The general trade-off between spectral and spatial resolution and Signal-to-Noise ratio will be discussed too.

IRIS instrument parameters:

Spectral Range	200 - 2000 cm ⁻¹ (5 - 50 μm)
Spectral Resolution	2.4 cm ⁻¹
Field of view	circular, 4.5 degrees full angle
NESR	3 to 5 x 10 ⁻⁸ W/(cm ² sr cm ⁻¹)

Introduction: Orbital spectral measurements of the volatile (CO_2 , H_2O) polar caps of Mars can potentially answer many questions about the current climate, and the inventory and transport of volatiles and dust. These, in turn, can address questions related to past and future climates and the ultimate reservoir sizes for volatiles. The observations in the polar night require thermal infrared or active instruments (that provide their own illumination). However, the most diagnostic bands for both CO_2 and H_2O occur in the solar reflected wavelengths $<5\text{ }\mu\text{m}$ and are easiest to measure after spring sunrise.

Background and Rationale: A significant fraction of the $\sim 6\text{ mbar}$ CO_2 atmosphere of Mars condenses onto the winter polar regions each year. This process brings into and releases from the polar latitudes significant, but largely unknown amounts of dust and water ice. If the net balance of these materials is positive, they can accumulate in perennial water ice and dust polar caps such as are observed in the summer north pole [1]. Using summer surface temperatures, however, it has been determined that the exposed south residual cap appears to remain covered by CO_2 [2, 3]. In addition to net accumulation, the dust and water ice added to the seasonal CO_2 cap have potentially large effects on the net radiative balance during condensation and sublimation [4], and hence on interannual atmospheric pressure variations and on the net accumulation of CO_2 such that it can last throughout the summer. Orbital spectra of the polar caps can potentially measure the concentration of dust and water ice in the optical surface and constrain the dust and water ice fluxes and determine the radiative energy balance. A determination of the dust concentration in the summer north cap could provide a highly valuable constraint on the important water-to-dust ratio [5] and therefore the water reservoir capacity of the perennial cap [6]. Estimates of the typical surface deposit grain sizes can also be made; they should be strongly related to measurable properties of the surface such as the thermal inertia.

Instrumental Requirements:

Thermal: Thermal radiation from the winter poles is more or less restricted to wavelengths longer than $10\text{ }\mu\text{m}$, depending on instrument signal-to-noise (S/N). Although significant radiation continues to $>200\text{ }\mu\text{m}$, it is unclear whether any significant information can be extracted from $\lambda > 50\text{--}60\text{ }\mu\text{m}$ (see, however, [7]). Although dust and CO_2 ice have strong spectral contrast in this region, the emissivity of surface water ice

typically varies by only $<5\%$ except for the smallest grain sizes. As such it is very difficult to accurately analyze water ice grain sizes or dust mixing ratios using only thermal spectra, even if the temperatures are warm enough that spectra are useful to $\sim 7\text{ }\mu\text{m}$. For the purposes of studying the surface properties, spectral resolving powers ($R = \lambda/\Delta\lambda$) ≤ 100 are more than adequate, but the optimal separation of atmospheric gas and aerosol signals from a top-of-atmosphere spectrum may well require higher values.

Solar reflected: In the visible and near-infrared wavelengths, all the polar materials have significant and contrasting optical properties, so remote sensing of both mixing ratios and microphysical state is very feasible. For $0.3 < \lambda < 1\text{ }\mu\text{m}$, both ices are bright and white, while dust is dark and red. In the infrared both ices have strong bands whose shape is strongly dependent on particle size while dust is mostly featureless, except for a possible $2.7\text{-}\mu\text{m}$ hydroxyl absorption. Except for the finest grain sizes, water ice is very dark $>3\text{ }\mu\text{m}$, but there is a well characterized variation of the $1\text{- to }2.5\text{-}\mu\text{m}$ spectrum of water ice with temperature [8]. This can provide information independent of thermal measurements if the spectrum is well resolved and the grain size is $<1\text{ cm}$. Resolving power requirements can be quite stringent in this region. $R \approx 100$ is adequate for visible measurements, while $R \approx 300$ is needed to resolve water ice features in the infrared, and $R \approx 5000$ may be needed to fully resolve the features of CO_2 ice [9] and separate them from nearby CO_2 atmospheric bands.

Existing Data Sets:

Thermal: The substantial data sets are (1) the Mariner 7 Infrared Spectrometer (IRS), measuring $4\text{--}14.3\text{ }\mu\text{m}$, $R \approx 100$ (2) the Mariner 9 high-resolution ($R \approx 500$) infrared interferometer (IRIS), measuring $5\text{--}50\text{ }\mu\text{m}$, and (3) the Viking Orbiter 1 and 2 Infrared Thermal Mapper (IRTM) with four infrared surface-sensing broad-band channels covering $6\text{--}25\text{ }\mu\text{m}$. Mariner 7 was a flyby, and IRS provides only a handful of spectra of the south seasonal polar cap in the spring, but these are among the highest S/N measurements available, especially in the wavelengths $6\text{--}8\text{ }\mu\text{m}$. The IRIS was intended for atmospheric studies and had a large field of view and low S/N; its observations of the polar regions are limited and rarely discussed. The IRTM instruments provide infrared coverage at generally high spatial resolution over large parts of two Martian years, but the information available from the broad-band sen-

sors is limited for several reasons. Only two of the surface channels are usable during polar night, making it, for example, impossible to distinguish between variations in grain size and variations in dust content of CO₂ frosts [10].

Solar reflected: Broad band measurements by cameras on Mariners 6, 7, and 9 and the Viking Orbiters, and the solar channel on Viking IRTM provide very limited information in the visible and near-infrared (for IRTM) range. Only the Viking cameras give us any significant narrow-band color observations, but very few polar observations were made using color filters. The infrared imaging spectrometer on the Phobos spacecraft only observed the equatorial region, but the short wave channel of the Mariner 6/7 IRS took 1.9–6 μm spectra ($R=100$) of Mars during two flybys. The Mariner 7 spectra of the spring polar cap are unique and valuable [11].

Current and Planned Data Sets:

Thermal: The thermal emission spectrometer (TES) on Mars Global Surveyor (MGS) observes a similar spectral range (6.5–50 μm) as the Mariner 9 IRIS, but with a much greater spatial resolution and improved S/N, at the expense of reduced spectral resolution (by a factor of 3–6). TES has already revealed new properties of the polar caps [12], and has the potential for much more, over the planned mission of ~1 Mars year. The broad spectral features in the thermal allow for less precise analysis than is possible using the finer bands in the near infrared, but the capabilities are still very much improved over IRTM. The infrared radiometer (PMIRR) on Mars Climate Observer (MCO), is designed for atmospheric studies, but observations of the surface are planned with broad-band sensors similar to IRTM. However, PMIRR has two channels with $\lambda > 30 \mu\text{m}$ and will be in a low orbit; it could outperform IRTM in polar studies (given sufficient S/N). The Mars 2001 infrared radiometer (THEMIS) has several narrow filters in the 6.5- to 14.5- μm region intended for mineralogical studies and is not well suited for polar observations where this region is more or less dominated by dust. The planetary Fourier spectrometer (PFS) on the ESA's Mars Express mission (2003) has a channel comparable in spectral range (5–43 μm) and field of view to IRIS, but should have much improved S/N.

Solar reflected: The imaging (~0.4–1 μm) cameras on current and future Mars missions have varying qualities. Mars Orbiter Camera (MOC) on MGS has a two-color wide-angle camera and a monochromatic narrow-angle camera, and may only be useful for determining the distribution of bright and dark regions on the poles. The color imager (MARCI) on MCO has a wide-angle, five-color camera, mainly for atmospheric

observations and a narrow-angle, 10-color camera designed for color surface imaging. A camera is also being prepared for the 2001 orbiter similar to the narrow-angle MARCI camera, as well as a stereo camera for the Mars Express mission. These instruments will all potentially be able to eclipse previous color imaging of Mars, but downlink volume constraints may limit the amount of multi-color data taken. Finally, both an imaging, visible to near infrared (0.4–5.2 μm , $R \geq 100$) spectrometer (OMEGA) and the short-wave channel (1.2–5 μm , $R=2500$) of PFS, will be flown on Mars Express. These instruments have the unprecedented potential of observing Mars over a very broad spectral range and at two resolutions. However, the elliptical orbit of Mars Express may limit the number and quality of observations in the polar regions.

Future Measurements: Most of the substantive studies dealing with the physical properties and energy balance of the polar caps have used Viking IRTM data [1, 3, 13, 14], but these works will find likely improvement with the spectral data needed to separate the contributions of atmosphere, water ice, dust and CO₂ ice [12]. The spring polar caps are covered by a warm atmosphere laden with aerosols, which complicate the thermal spectra to an extent that it becomes difficult to separate the surface spectrum. This task should be substantially easier using near infrared reflection spectra [11], but we must wait until 2004 for this. A synergistic study with high spatial resolution color imaging and both near and thermal infrared spectra with suitable spatial and spectral resolutions is most desirable for addressing Mars polar questions. Only the planned Mars Express mission, if it continues and is successful, appears to offer this prospect. Given the current uncertainties in project funding and hardware failures, it would seem prudent to plan another mission of this sort, if at all possible.

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1969 MARINER MARS INFRARED SPECTROMETER: LESSONS FOR FUTURE EXPLORATION.

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Introduction: Spectra returned by the 1969 Mariner Mars Infrared Spectrometer (IRS, 1.8 - 14.2 μm) have been used in a range of studies of the surface composition of Mars. IRS measured a wide spectral range with good spectral resolution and excellent signal to noise ratio (SNR). Table 1 lists spacecraft spectrometers that have returned spectra of Mars.

IRS results, as well as a comparison of IRS, the 1971 IRIS, 1989 ISM, and 1997 TES spectra show that an unambiguous examination of the surface mineralogy of Mars requires: (1) high spectral resolution ($\sim 2\text{-}5\text{ cm}^{-1}$ in the thermal region, and $\sim 10\text{-}20\text{ cm}^{-1}$ in NIR); (2) high SNR (>600); and (3) continuous spectra measured of the VIS-NIR, overtone, and fundamental regions. Radiometer measurements, such as those provided by Viking IRTM and the proposed 2001 THEMIS, can be used to map spectral type regions. However, fully utilizing a radiometer data set will require complementary high quality spectra for an unambiguous examination of the minerals present.

Instrument: IRS used two circular variable interference filters with $\sim 1\%$ resolution to scan continuously two channels, from 1.8 to 6.0 μm and 3.7 to 14.2 μm [1]. Each spectrum contains approximately 1340 discrete measurements, scanned every ten seconds.

Continuous spectrum: Huguenin [2] noted that the assignment of a single band is frequently ambiguous, while the assignment of a suite of bands is generally not. Continuous spectra such as those recorded by IRS allow an examination of more than one spectral region and feature, and so the least ambiguous study of surface mineralogy.

Spectral range: The infrared spectrum can be divided into three approximate ranges that exhibit distinct behavior: *VIS-NIR*, (0.4 - $\sim 3\text{ }\mu\text{m}$); *overtone*, ($\sim 3\text{-}7\text{ }\mu\text{m}$); and *fundamental*, ($\sim 7\text{-}50\text{ }\mu\text{m}$). Each region contains complementary information. The information content of a spectrum increases significantly when it covers more than one spectral range.

VIS-NIR region. This region measures mainly reflected light (0.4 - $3\text{ }\mu\text{m}$). It is simpler to use for quantitative measurements of mineral abundance, and atmospheric corrections are also simpler than for thermal wavelengths. IRS shows that this range can be combined with thermal wavelengths to provide more information on the surface than either wavelength range alone [3].

Overtone region. This region ($\sim 3\text{ - }7\text{ }\mu\text{m}$) is particularly important for studies of Mars because finely-particulate minerals, such as those predicted to occur on Mars, commonly have strong, diagnostic overtone features, but very weak fundamental features (which

occur at longer wavelengths) [4]. This region is analogous to the hydrogen-oxygen overtone region at shorter wavelengths.

IRS spectra provide unique, high quality coverage of 3 to $7\text{ }\mu\text{m}$, and they show this region is relatively uncomplicated by aerosol dust features. For thermal infrared studies of Mars, the aerosol dust greatly complicates an investigation of the fundamental regions, especially $\sim 8\text{-}13\text{ }\mu\text{m}$, where the aerosol has a particularly strong band. However, in the overtone region, silicates lack strong transmission features. This simplifies any study of this spectral region, and increases confidence in the results. The composition and particle sizes present can be better constrained using a combination of the overtone and other spectral regions than it can using only one region.

Fundamental region. Finely particulate materials such as those predicted to be present on Mars commonly have very weak fundamental features ($\sim 7\text{-}50\text{ }\mu\text{m}$). Fundamental bands generally become weaker as particle size decreases, while overtone bands become stronger [4]. The fundamental region is most suitable for examining the mineralogy of larger particle sizes, while the overtone region is better for finely particulate materials.

Spectral resolution: Atmospheric constituents interfere with measurements of the surface spectrum, but the interference decreases with increasing spectral resolution. Measurements with higher spectral resolution contain additional detail that allow the best separation of atmospheric and surface absorptions, and the most accurate definition of band shape, center, and width (Figure 1). Figure 1 shows that the $12.6\text{ }\mu\text{m}$ (790 cm^{-1}) atmospheric CO_2 band broadens and distorts spectra with decreasing spectral resolution. As a second example, an examination of TES spectra in the $18\text{-}23\text{ }\mu\text{m}$ region requires an atmosphere removal [5], while IRIS spectra can be examined more directly.

A correction can be applied to reduce the distortion of surface features by atmospheric bands, but such corrections are never perfect. The accuracy and reliability of the correction decreases with decreasing spectral resolution, and it is especially difficult to apply to data returned by a radiometer. An atmosphere removal complicates the data processing; makes it more costly to perform; makes it take longer to obtain results; limits the accuracy and acceptance of the results; and it limits the number of researchers who have the time and resources to utilize the spectra. The most timely and accurate results are obtained with spectral resolution high enough to measure points that "see between" the

atmospheric gas features, and thus have minimal interference from atmospheric gases. This allows a more direct fingerprinting of the mineral present.

Signal to noise ratio: Spectra should have sufficient SNR so features present in a single spectrum can be trusted. The alternative is averaging the spectra, but this decreases their spectral or spatial resolution. For example, IRS spectra remain of great value because of their high SNR, especially for $<7\ \mu\text{m}$. TES has lower SNR, and struggles at the shorter wavelengths. IRIS has the lowest SNR, and usually requires some form of

averaging even for day measurements. The 2001 THEMIS should have a SNR comparable to IRIS [6].

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Table 1: Spacecraft spectrometer parameters.

	1989 ISM ^f	1969 IRS	1971 IRIS ^b	1997 TES ^c	2001 THEMIS ^k
wavelength range (μm)	0.77 - 3.1	1.8 - 14.4	5 - 50	~6 - 50	6.5-15.5
spectral resolution at $10\ \text{cm}^{-1}$	—	$10\ \text{cm}^{-1}$ (1%)	^h $1.2\ \text{cm}^{-1}$ (0.12%)	^h 10 or $20\ \text{cm}^{-1}$ (1 or 2%)	—
optical path difference (cm)	—	—	0.85	0.1 or 0.05	—
measurements per spectrum	64	1340	1500 ^g	143	9
approx. measurements per resolution element	2	5	2	2	—
spatial resolution (km)	25	130-500 ^d	125-1000	3 ^a	0.1
SNR ($2.2\ \mu\text{m}$) ^a	400	190	—	—	—
SNR ($6\ \mu\text{m}$) ^a	—	340	18 ^e	low	—
SNR ($10\ \mu\text{m}$) ^a	—	600	100	400	—
SNR ($25\ \mu\text{m}$) ^a	—	—	400	good	—

^aValue is rms at 270K (thermal), or for a typical bright region (NIR). ^b[7]. ^cTES also has one thermal and one reflectance broadband channel [8]. ^dFrom mapping orbit of 350 km. ^eIRIS SNR from [9]. ^f[10]. ^gIRIS measured interferograms with 4096 points [7], but these have been lost; what remains are spectra with 1500 points per spectrum. ^hIRIS and TES values are unapodized, both calculated as $1/\text{optical path difference}$. ^k[6].

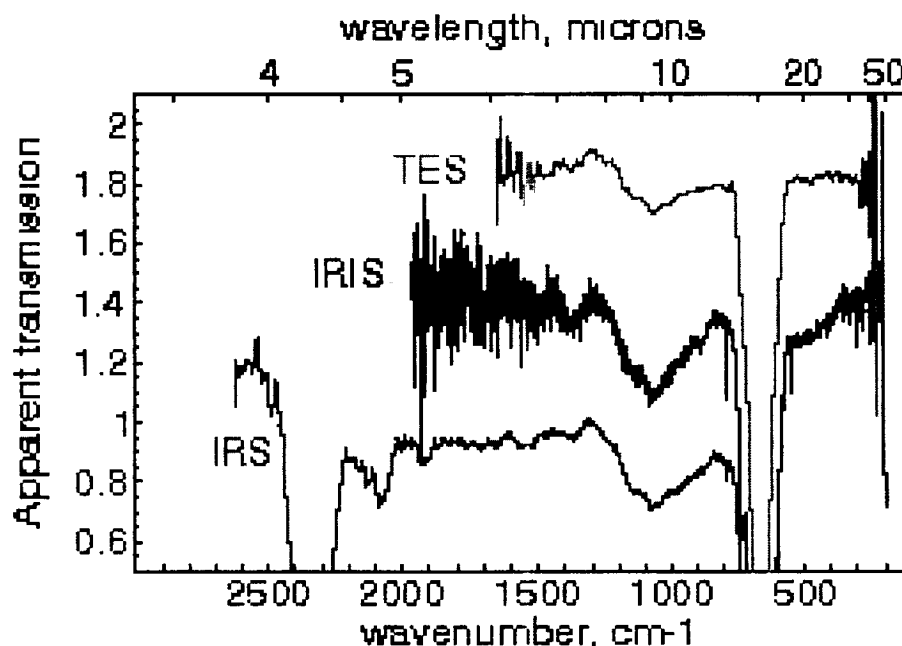


Figure 1: Comparison of typical IRS, IRIS, and TES spectra. IRS has the highest signal-to-noise ratio, especially at the shorter wavelengths. IRIS has the highest spectral resolution, which can be seen here by the sharp atmospheric lines present in IRIS spectra. For example, note the difference in appearance of the CO_2 gas feature at $12.6\ \mu\text{m}$ ($790\ \text{cm}^{-1}$) between the different data sets. IRS also measures to $1.8\ \mu\text{m}$ ($5500\ \text{cm}^{-1}$), but the spectra are not yet calibrated. TES measures with the highest spatial resolution.

THE SEBASS HYPERSPECTRAL IMAGING SPECTROGRAPH: INSTRUMENT DESCRIPTION AND SAMPLE THERMAL IMAGES OBTAINED NEAR FLAGSTAFF, ARIZONA AND MESQUITE, NEVADAEric R. Keim, Space and Environment Technology Center, The Aerospace Corporation, El Segundo, CA, <eric.r.keim@aero.org>.

The Aerospace Corporation's SEBASS hyperspectral imaging spectrograph uses two 128 x 128 focal-plane arrays to record simultaneous LWIR and MWIR images (7.8 to 13.5 and 3.0 to 5.5 μm). The resulting thermal images can be used for characterization and identification of surface geological features. A brief description of the instrument and its operation on a DeHavilland Twin Otter aircraft will be given, followed by the presentation of preliminary results from data collections over Flagstaff, Arizona and Mesquite, Nevada.

REVIEW OF THE ISM INSTRUMENT AND RESULTS. John F. Mustard, Department of Geological Science, Box 1846, Brown University, Providence RI, 02912. (John_Mustard@brown.edu) #3040

Instrument Parameters: Detailed descriptions of the ISM instrument are provided by [1,2,3,4, 5]. The ISM instrument is a scanning imaging spectrometer that covers the spectral range 0.76 to 3.16 μm . For each pixel, 128 spectral measurements are acquired simultaneously. A 2-dimensional image of the surface was obtained by rotating the entrance mirror to scan in the cross track direction for the image samples and the forward motion of the spacecraft provides the image lines. The spectral dispersion is obtained by using a grating, whose the first and second orders are exploited. These two orders are separated by a beam-splitter and filters, and measured by four groups of 32 cooled PbS detectors, designated first and second order odd and even. Extensive evaluation of data quality and integrity has shown that the even detectors are superior overall to the odd detectors [4]. Therefore the even channels for the first and second order are used which results in 64 channel spectra for each pixel. The signal to noise of these data is extremely high and averages greater than 500:1 for data from 0.77 to 1.51 μm and 1.68 to 2.6 μm . The detector sensitivity drops off slightly at the extremes of the wavelength ranges, but only drops below 100:1 at wavelengths longer than 2.6 μm .

The ISM experiment acquired 11 imaging spectrometer data sets for the surface of Mars. These data sets, or windows, are 24 samples wide and up to 120 lines long. The IFOV of the instrument is 12'x12' which, from the altitude of orbit of 6300 km, corresponds to a surface resolution of approximately 22x22 km at normal incidence. In the rest position, the viewing plane of the instrument was oriented parallel to the sun's rays and therefore at the subsolar point, the incidence angle equals the emergence angle and the phase angle is 0°. The scanning mirror permits some variation from this geometry and the phase angle varies <5° for each window and is always less than 20°. Incidence and emergence angles are a function of longitude and latitude. The image data for a given window were acquired over a period of 25 minutes and therefore the effects of temporal variability in the atmosphere are minimal. There is a systematic increase in atmospheric path length with distance from the subsolar point.

Strengths of the Data Set: At the time the data were acquired, ISM constituted the first imaging spectrometer data set acquired of another planet from orbit. The key strengths were the contiguous spatial pixels, the imaging format, and most importantly the SNR. The importance of the imaging format cannot be overemphasized, as this allowed checking of spectral feature mapping, and mapping of spectral properties of the surface across boundaries and geologic units. The calibration of ISM has been extensively studied and refined over time [4, 6, 7], but what allowed this to a large extent was the very high quality of the acquired data. However, the very high SNR allowed many

analyses of relative surface spectral properties to proceed regardless of absolute calibration.

Significant Results: There have been 27 peer reviewed publications which concentrate on the data from the ISM spectrometer for Mars and Phobos [5] covering topics ranging from the atmosphere (including composition, aerosols, and variability), to the surface composition (mafic mineralogy, hydrated mineralogy, unusual materials), to the scattering of the surface. Important null results were the lack of any carbonate, sulphate, scapolite, or distinct clay features.

Atmosphere: The atmospheric opacity during the mission was uniformly low, estimated to be 0.2 - 0.3 [8, 9] while atmospheric H₂O showed a diurnal variability [10]. Detailed studies of aerosols revealed several important properties [7]. Scattering by aerosols and dust in the atmosphere is a function of atmospheric opacity and the ISM data were acquired during the period when atmospheric opacity is generally at its lowest. The magnitude and spectral characteristics of the atmospheric scattering were derived for the ISM data using two methods. The first used several spectra that were obtained of the limb permitting direct measurement of atmospheric scattering. The second method made use of regions which were measured during different observing runs. The results of this analysis are that the aerosol particles have an average radius of 1.2 +/- 0.2 μm . The spectrum of the aerosol contribution is dominated by a negative continuum slope which decreases exponentially toward a minimum near 2.6 μm . In addition, the spectral properties revealed a component of water ice, likely associated with atmospheric dust particles.

The total relative contribution to the surface signal is estimated to be 5-15%. Since this scattering is additive, analysis of differences in spectral slope between terrains due to surface spectral properties through derivatives (e.g. [6, 11]) is valid. This scattered component affects the position, shape and strength of mineral absorption features in two ways. First, absorption band strength is reduced which may explain why important crystalline ferric absorptions are observed at some times (e.g. [12]) but not others (e.g. [13,14]). The second effect is to cause an apparent shift to longer wavelengths of absorption band minima. This shift is small (<10-30 nm) and does not significantly change previous analyses of surface composition from ISM data, but should be factored into future analysis of surface composition from absorption band position and shape.

Mineralogy of Low Albedo Regions: The high spatial resolution, spectral coverage, and high signal to noise of the ISM data permitted the determination of a mineralogic basis for the spectral properties of several distinct morphogeologic dark regions on Mars [15, 16]. Through the use of the Modified Gaussian Model, it was shown that these areas are dominated by two-pyroxene basalts, analogous to the basaltic SNC

meteorites, but that the plateau plains (e.g. Syrtis Major) are enriched in high-calcium pyroxene relative to the floors of Valles Marineris. Within this two-pyroxene model, there exists significant diversity in the spectral properties among relatively unaltered regions on Mars, and a central question is how is this spectral diversity related to mineralogic diversity. Then, once we understand the mineralogic composition, what does that tell us about volcanic processes and the composition of the source regions. Ultimately, however, the presence of two-pyroxene basalts implies they were derived from mantle depleted in aluminum relative to the original mantle composition inferred for Mars.

Mineralogy of Bright and Transitional Regions:

While bright regions show a greater homogeneity than dark regions, they also exhibit important information related to their mineralogy. Murchie *et al.* [17] showed that the bright regions are largely consistent with the nanophase hematite model in an amorphous silicate matrix. However, most regions exhibited a very weak 2.2 μm feature consisted with a metal-OH band. Some regions, however, did not show this feature. In addition, there are significant variations in the strength of the water of hydration band near 3.0 μm , where layered terrains in Valles Marineris exhibited the strongest absorptions. Finally, many of the so-called dark red regions (e.g. Oxia Palus) exhibited features inconsistent with a simple mixture between bright and dark soils. Rather, they appear to be a unique material and may contain hydrated ferric oxides and oxyhydroxides.

Weak Points of the Instrument and Data Set:

Perhaps the single largest problem to plague the ISM data set was calibration. There are several reasons for this. First, the instrument did not have as extensive an instrument check out as it could have. This is not a criticism of the personnel at IAS who did a remarkable job under a very tight schedule. However, several problems were revealed once the instrument arrived in orbit and it was necessary to conduct numerous analyses to identify and correct calibration problems. While these operations were ultimately successful, it resulted in a distrust of the data set by the larger community. Nevertheless, two studies showed an excellent agreement between ISM and independently acquired spectral data sets [18, 19]. Another weakness was spectral resolution. Although the instrument did have 128 channels, only 64 were used due to pointing and calibration. In addition, slight channel-to-channel offsets created artifacts in limited spectral regions at particular albedo boundaries. Finally, the lack of visible spectral information seriously hampered the ability to understand the ferric mineralogy and separate it from ferrous mineralogy.

Lessons Learned: ISM demonstrated the great value of imaging spectroscopy for Mars exploration. Despite the calibration criticisms, and the fact the Mars is remarkably homogeneous on a global scale, much important information was obtained. The extraordinary

SNR permitted analysis of the calibration and the mapping of extremely subtle spectral differences on the planet. The most exciting features that unfortunately could not be pursued due to the lower SNR were in the water bands near 3.0 μm . There were distinct variations on the surface related to geologic features, but they were slightly beyond the spatial and spectral resolution. In my opinion, these are the most important items to consider for future missions:

- Signal to noise...sacrifice spectral and spatial resolution for signal to noise (to a point).
- Spectral range...cover the visible and near-infrared out to the 4.0 CO₂ band
- Spectral resolution...at least 10 nm in key wavelength regions.
- Calibrate, calibrate, calibrate!

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ALADDIN INSTRUMENTS AT MARS. Carlé M. Pieters¹, John F. Mustard¹, and Scott L. Murchie²,
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The primary goal of the Aladdin Discovery mission is to obtain samples from both satellites of Mars and to characterize the geology of these two small bodies in detail. Aladdin carries a suite of remote sensing instruments designed to map the surface composition of the satellites and to place the samples in geologic context. While Aladdin is in the Mars environment, there is also ample opportunity to acquire valuable spectroscopic data for Mars. Aladdin carries substantial memory (32 Gb) which allows storage of large amounts of Mars remote sensing data. The mission sequence allows transmission of this data to be spread over the active period at Mars plus the return journey to Earth. A near-lossless hyperspectral compression algorithm will allow acquisition and downlink of at least 52 Gb (uncompressed) of hyperspectral imaging data. The prime mission activities occur in 2005; an overall mission summary can be found in Pieters et al. (1999, LPSC 30).

The optical instruments that constitute Aladdin's remote sensing payload are summarized in Table 1. The two instruments of interest to Mars science objectives are CCAM and ISPEC. Both have a similar FOV (1.5° and 1.4° respectively), but CCAM has a higher spatial resolution/pixel (25 μ rad vs 100 μ rad). ISPEC is particularly well suited for detecting and mapping minerals indicative of past aqueous environments of Mars (Figure 1). A discussion of applications for Mars can be found in Mustard et al. (1999, LPSC 30). Figure 2 is a comparison of spatial resolution and spectral coverage illustrating how ISPEC fills an important void in planned Mars observations. The design features for ISPEC are summarized in Table 2 and the optical layout and cut-away model shown in Figure 3.

The entire equatorial region of Mars will be available for measurement at Aladdin's orbital distance from Mars (~6000 km). Optimal viewing conditions (phase angles of <30°) are available on all measurement orbits. ISPEC will map surface mineralogy of Mars for swaths ~150 km wide with a resolution of 600 m/pixel. The areal coverage attainable will depend on the compression ratio employed. For a conservative 4:1 compression, vis-nearIR hyperspectral image cubes will cover 13% of the Mars surface. During Phase B of Aladdin an *ad hoc* Mars Advisory Committee will be formed to assist in the development of an observation plan and to prioritize Mars observations for optimal science return.

Table 1. Aladdin Optical Instruments

Instrument	Function
ISPEC Imaging Spectrometer	Characterize and map mineralogy, hydrated species, organics (230 channels: 0.4 - 3.6 μ m)
CCAM	Map spectral units; 8 filters 0.4 - 0.9 μ m
NAVCAM	Morphology, topography; perform precision targeting
PCAM	Image the regolith plume

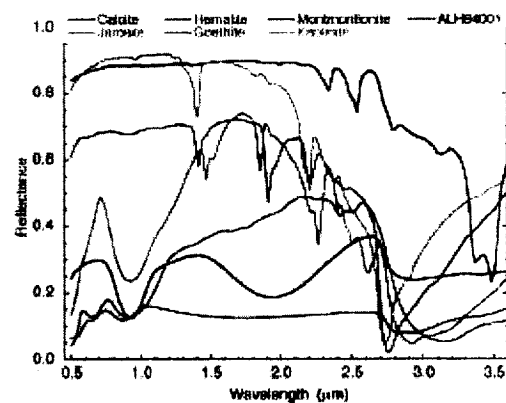


Figure 1. Reflectance spectra (ISPEC spectral range) of minerals indicative of different Mars environments.

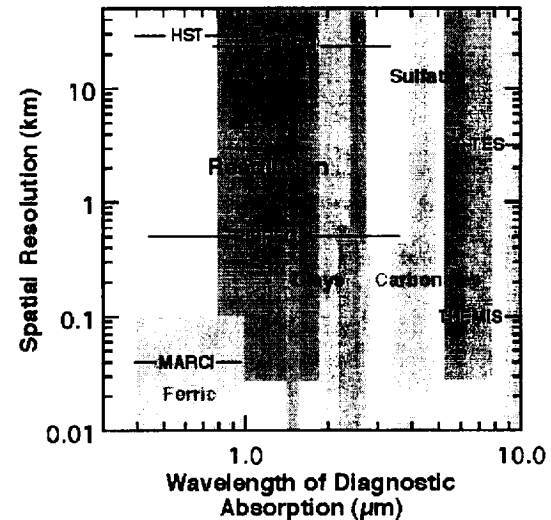
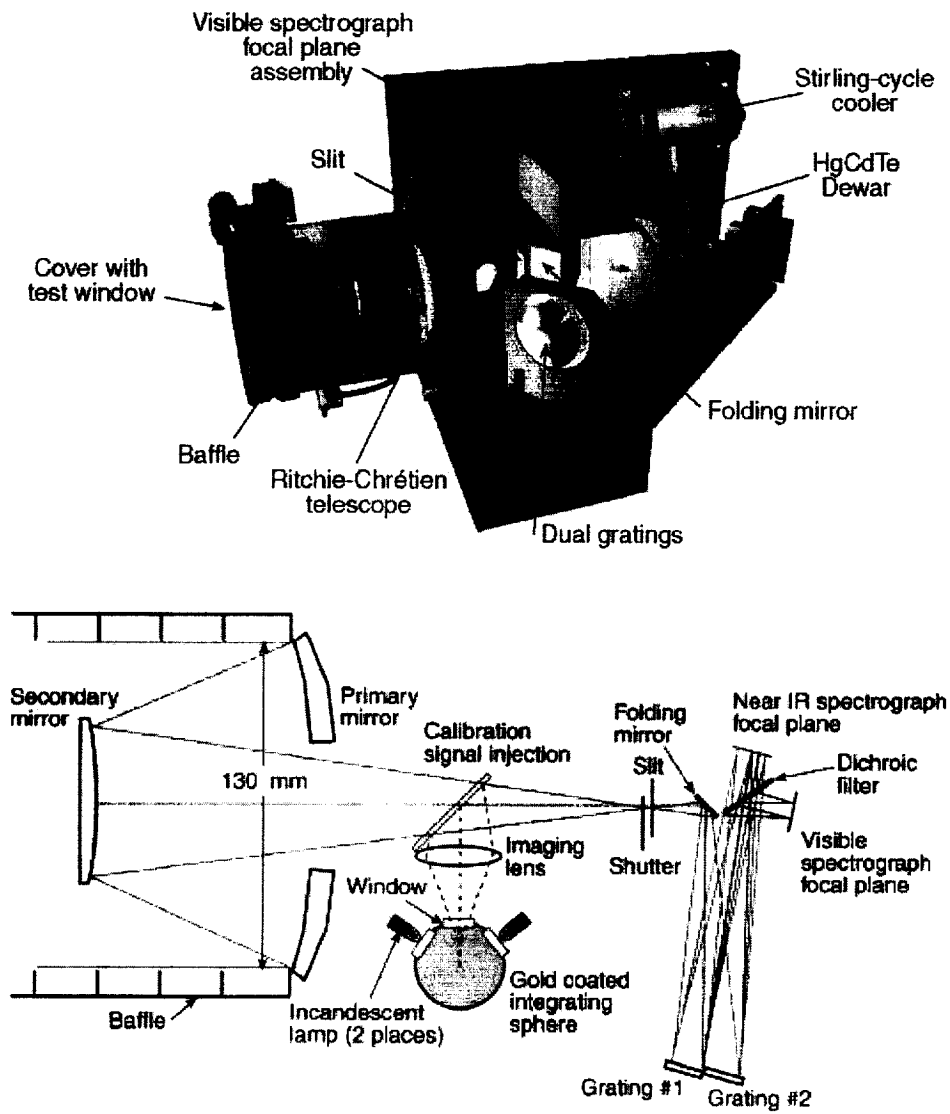


Figure 2. Relation of Aladdin's ISPEC vis-NIR measurements to other remote sensing observations of Mars. Colored regions show wavelengths of absorptions diagnostic of minerals that indicate past wet environments, and spatial scales of occurrence.

Table 2. Aladdin ISPEC Design Features

	Telescope	
Aperture	130 mm diameter	
Focal length	422 mm	
FOV	1.4°	
	Visible to Near-Infrared	Near-Infrared
Detector	CCD 1024x1024 pixels, binned 3x3	HgCdTe 256x256 pixels
Pixel FOV	100 μ rad	95 μ rad
Spectral Range	450-1050 nm	900-3600 nm
Spectral Resolution	10 nm @450-1050 nm	20 nm @900-1800 nm, 10 nm @1800-2600 nm 20 nm @2600-3600 nm
Spatial Resolution	244 pixels, 600 m @6000 km	256 pixels, 570 m @6000 km

Figure 3. Aladdin ISPEC optical layout and model.



USE OF THERMAL HYPERSPECTRAL IMAGERY IN TERRESTRIAL SURFACE CHARACTERIZATION Stephen J. Young, Space and Environment Technology Center, The Aerospace Corporation, El Segundo, CA, <stephen.j.young@aero.org>.

Hyperspectral imagery collected in the LWIR atmospheric window region from 8 to 13 μm with the Aerospace Corporation's SEBASS sensor have been used in preliminary assessments of terrestrial surface characterization. Example applications will be presented showing the capability for soil and mineral identification and mapping. An overview of the mathematical algorithms employed will be included. For terrestrial applications, best results are always obtained using target spectra obtained from samples collected from the survey site. Variations of the method suitable for unobtainable site samples will be illustrated and discussed.

